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System Instantiation Comparison Method: A Technique for Comparing Military Headquarters

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ABSTRACT

This document provides a generic, efficient and cost-effective method of comparing system instantiations. It gives a unique view of a complex system by considering how well the system supports the overarching aim. The method proposed was developed from a requirement to undertake evaluations of complex military systems, in particular those associated with command and control. To illustrate the generic nature of the method, it is introduced using three very different systems. A military headquarters is then used as a more comprehensive example of how the method can be applied.

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Executive Summary

Investigating complex systems, such as a military headquarters, poses a challenge, not only in terms of generically defining the system, but also in providing a flexible and cost-effective way of comparing similar types of systems. Introducing new technologies adds further complexity to this problem. Many methods and techniques have been developed to evaluate systems. However these are process orientated and output driven, focusing on the quality of the outputs and processes of the system. These processes can, and usually do, change from one system of a similar type to another, they are not always generic in nature and may not even add to the overall goal of the system. Hence, using these methods to make comparisons between similar types of systems is difficult. A new way of viewing a complex system and providing techniques for the comparison of system instantiations is required. This document introduces such a system instantiation comparison technique.

In systems methodologies, the system instantiation comparison method is aimed at use in analysing complex systems; in particular, those systems where there are multiple decision makers who do not all have the same goal or understanding of the current situation. What is unique about the method is the view that it takes of the system. Here, a complex system is defined in terms of how 'well' it allows you to achieve its operational objectives. This places no judgement on the quality of the outputs or the processes of the system. The method described defines a generic system in terms of its variable and static properties providing a foundation for comparative evaluations. It defines a complex system in simple terms and provides a way of quantifying the different options for the same type of system, thus allowing for a direct comparison between instantiations. It also provides a scaling ability for the level of detail in the application of the method; if required, more detail can be included in subsequent studies. Due to the way the system is defined by the method, comparisons of instantiations are considered by the authors to be efficient and cost-effective.

The method proposed was developed from a requirement to undertake evaluations of a complex military system, in particular evaluations associated with military command and control and the introduction of new technology. The method is first introduced using three very different systems to illustrate its generic nature and flexibility. A military headquarters is used as a more comprehensive example of how the method can be applied. Generic characteristics associated with the information and the functions used by a military headquarters, as defined by the authors, are used as the basis to represent the system. System measures associated with different instantiations were obtained and rated.

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1. Introduction

Complex systems by their very nature are difficult to evaluate. The problems lie in defining the system in such a way as to provide a flexible and cost-effective comparison of similar systems. A new way of viewing a complex system and providing techniques for comparing system instantiations¹ is required. This paper introduces the System Instantiation Comparison (SIC) method, intended to meet the shortfall in the currently available techniques.

The method was developed to meet a requirement to provide a simple, flexible and cost-effective approach with which to compare complex military systems, such as command and control, so that changes, such as the introduction of new technologies, in these systems can be quantified. However, the method can also be applied to the examination of a broad class of systems that are not necessarily military, for example biological systems. It should be noted that the method has been designed to facilitate the comparison of instantiations of a system, not to give an absolute value of the system. That is, it will not give the analyst a quantitative outcome such as 'this system is 10% effective'.

First, a review of existing techniques, highlighting deficiencies for the analysis techniques for complex systems is presented. This clearly demonstrates the need for a new approach to viewing and evaluating complex systems. Next the SIC method is introduced in a general context using several examples of complex systems to illustrate the concepts. This is followed by a more in-depth application of the method to the analysis of a military headquarters. Finally, some concluding remarks and comments on future directions of this research are outlined, including an overview of where it has been applied in practice.

2. An Overview of Primary Existing Methods

There are many different system analysis approaches described in the literature. One way of helping to determine the most appropriate technique for a given problem is to use a problem classification technique as defined in Flood and Jackson (1991). In this classification, the state space of problems is defined as a 2-D space. One axis is labelled with simple and complex and the other with unitary, pluralist and coercive². Thus, using the guidance given in Flood and Jackson (1991), a problem can be classified to a given section of problem space and an appropriate analysis method applied. The SIC method is aimed at use with complex pluralist systems, although it is also applicable to complex unitary and, in a more limited fashion, to complex coercive systems.

Prior to the development of the SIC method, many other techniques were investigated by the authors. None of these were considered to fully satisfy the analysis needs. The

¹ An instantiation of a system is a particular variant of the system.

² Definitions for each of these can be found in Flood and Jackson (1991).

following is a brief outline of some of these approaches, suggesting the relative merits and weaknesses of these techniques as applied to the comparison of complex system instantiations.

The soft systems approach is a technique that is growing in popularity and provides a descriptive platform on which to base the investigation of systems (Checkland 1993; US DoD 2000a; US DoD 2000b; Finegan 2000; Lane and Galvin 1999; and Soft Systems 2000). A pictorial representation of the system through the use of conceptual models provides the analyst with an impression of the prevailing trends within the organisation. The use of rich pictures provides descriptions of the system's tasks and how it performs them. However, this method lacks the ability to easily provide a quantitative measure on which to conduct investigations due to its descriptive nature.

Knowledge-based system development (ARTI 2000) builds a number of separate models that capture salient features of the system and environment, including: organisational; task; agent; communication; and expert and design models. It is process based and does not lend itself to providing a complete view of the system; rather it provides many views of the system. This is good in that it gives insight into aspects of the system, but it does not give a good idea of changes to the system as a whole.

Quality Function Deployment is a conceptual map that provides the means for cross-functional planning and communications (Jagdev, Bradley and Molley 1997). It is a method for transforming customer wants and needs into quantitative, engineering terms. This technique focuses on the characteristics of an organisation's products and services. These characteristics are assessed and prioritised using the customer's or end user's point of view. The method is quantitative in nature, it does provide measuring parameters but does not provide a method for putting them into a single number to represent the system, limiting its ability to be used to compare system instantiations.

The structured systems analysis and design methodology is a typical structured method used in the analysis and design stages of systems development, but it is not well suited to the construction, testing and implementation stages (Uni. of Glamorgan 2000 and Universität Bremen 2000c). This method seems best directed towards software development or information systems engineering. The technique adopts a prescriptive approach to information systems development in that it specifies in advance the modules, stages and tasks which have to be carried out, the deliverables to be produced and the techniques used to produce these deliverables. The technique adopts the waterfall model (2000) of systems development, which uses a systematic sequential approach, where each phase has to be completed and signed off before the next can begin. The application of structured systems analysis and design methods are aimed primarily at the development of information systems on the basis of data base systems and less at the development of real time oriented software. The method concentrates on data flows and data models, which suggests that it is best suited for the investigation of the processes carried out by a system.

Functional decomposition, as defined in Universität Bremen (2000c), is more a philosophy of how to break down a system. The approach can be best summarised by the following

quote from Universität Bremen (2000c): 'the objective is to decompose a system step by step, beginning with the main function of a system and continuing with the interim levels down to the level of elementary functions. On each level, abstractions are made from each corresponding lower level. All the sub functions together form completely the decomposed function (functional hierarchy)'. This technique appears to be used in concert with other methods to produce a list of hierarchical elements rather than an evaluation technique. It provides components under which to view the system.

Data flow modelling, Universität Bremen (2000a), is used to define the functional structure of a system by means of the combined consideration of functions and data. The data flows are the interfaces between the functions. The data flow modelling abstracts from the physical facts of a projected system. It takes a top down approach, where more and more detailed levels of the future systems are specified. This is based on the context diagram, which only represents the data flows of the systems from and to its environment. When refining the data flow model, the functions are identified in the functional hierarchy (functional decomposition) and refined by means of the data flow diagram of the corresponding levels. The data flow diagram of a certain hierarchical level can be made to represent the incorporation of processes that are connected via data flows. A refinement of the data flow diagram is always realised in balance with the corresponding refinement of the functional hierarchy. This technique focuses on describing the processes used in a system and provides only limited evaluation as it is only concerned with the suitability of the data constructs.

Activity modelling develops an accurate description of the activities performed by the system. These models seek to discover 'what' needs to be done rather than 'who' does it, or 'how' it is done. They can be used to identify and organise the activities that a component of an organisation currently performs, or should be performing to achieve its objectives and goals independent of the organisational structure (Lonsdale 2000a, Lonsdale 2000b and Universität Bremen 2000b). This type of modelling can be considered to be a way of specifying or identifying the system objectives, but not to compare systems quantitatively.

Use cases are an informal and imprecise modelling technique, which can be used to define the fundamental structure of an application. They emphasise describing the events in the story of interaction between actors (external agents, which normally represent the roles of people) and a system (usually represents a software system) (Larman 1998 and Lonsdale 2000a and -b). Use case modelling cannot usefully be used to capture non-functional requirements. Nor can it be used to capture internal functional requirements. The use case model is about describing 'what' the system will do at a high level, but with a user focus for the purpose of scoping the project and giving the application some structure. Use cases are not a functional decomposition model and they are not intended to capture all of the system requirements. Use cases do not capture 'how' the system will do anything, nor do they capture anything the actor does that does not involve the system. All these things are better modelled using other techniques. The art of using this method is to identify the user goals not the system functions. Thus it is not a good technique for holistic system evaluations.

Some strategies, such as systems dynamic modelling (Coyle 1987; Coyle 1996; Kearney 1998; Coyle 1992; and Coyle and Millar 1996), are used to investigate system outputs, focusing primarily on factors associated with speed of operations. This type of examination focuses on the dynamic properties of the system and investigates its behaviour over time. Its strengths are in its representations of very complex systems to provide broad indications. Its weaknesses are in its oversimplification of the system's representation and reliance on time as its major measure. It is best suited to the investigation of strategic outcomes for the provision of first estimates to focus more detailed investigations.

Another technique having a time and process focus is discrete event modelling (Levis 1993). Generally discrete event modelling is used in conjunction with the functional decomposition to gain a model of a particular system. Often due to the way such models are constructed, it can be time consuming to change an existing model to represent a new instantiation, particularly if unplanned changes occur. This technique is time, process and output focused.

Techniques such as integrated computer aided manufacturing definition, and systems engineering (US DoD 2000a and -b) are designed to help evaluate systems, but from a descriptive viewpoint. Also they are very focused on the tangible outputs of the system in terms of their processes. They do not focus on the operational requirements of the system as a whole. Adjustments using these techniques are labour intensive. These techniques such as Integrated DEFinition language are a structured methodology for functional process analysis. They suffer from the complexity of the diagrams and distinguishing between the 'as is' system and the 'to be' system. Other problems include distinguishing between the controls and inputs defined for the methodology and establishing proper boundaries for the model.

The techniques described above have strengths and weaknesses, some of which are described in Richardson and Bartley (1998). Many are output driven, evaluating the system in terms of the quality of the outputs, allowing limited investigation of a system in terms of how well it supports the production of these outputs. They often focus on using the processes to define and describe the outputs and key elements of the system, rather than what the system is trying to achieve, and how best to achieve it. Focus also tends to be on certain aspects of the system rather than the system as a whole. The techniques often do not actually evaluate the system as a whole; they identify different aspects of it. They have the ability to provide descriptive snapshots, but struggle to quantify the evaluation of the system and to allow for comparison of system instantiations.

A major issue with analysing complex systems is the fact that such systems, due to their complexity, are variable in nature. This means that even for a given set of environmental conditions in which the system operates there are many possible outputs. So a complete analysis with any output based techniques is very expensive. Thus in general only a small fraction of the possible solutions can be investigated. Also, process based approaches define the system according to its most variable nature; the processes within the system. It is the processes that change constantly and are very dependent on the human elements of the system. If an extensive study is not carried out, then essentially only a snapshot of the

system will be obtained. This reduces the value of the study to the current analysis as well as the value it has to future evolutions. Consequentially, comparing the same system under different circumstances is nearly impossible with any great credibility and comparing similar types of systems can be even more problematic.

What is needed is a different view for defining the system and focusing evaluations; this is the unique nature of the SIC method. Here a complex system is defined in terms of how well it supports the achievement of the outcome, not on judging the quality of the output of the system. The SIC method defines a generic system in terms of its variable and static properties. The variable aspect of the system provides a foundation for comparative evaluations. It also provides a scaling ability for application of the method, if required; more detail can be included in subsequent studies. Finally it is independent of scenario, something that many methods are not. The techniques described above do not readily provide all of these capabilities. However, many of them do provide tools to assist in looking at certain aspects of the system and can be used in conjunction with the SIC method.

3. The System Instantiation Comparison Method

The SIC method was developed to allow complex systems to be clearly defined and quantitatively compared, in terms of supporting the achievement of an outcome, and its variable and static properties. The core idea behind the SIC method is to provide a viewpoint of a complex system in three parts. Two of these parts are defined by the system's operational requirements³ and are fixed for each system instantiation. The third provides the capability of the system to support these requirements. Once this breakdown has occurred, a system measure can be determined for different system instantiations. As with all modelling techniques, this method depends on the correct representation of the system being analysed. The method is considered independent of scenario. The operational requirement sets the context in which the system is investigated. However, the tempo with which the system is required to operate influences the evaluation of the system. Examples of this scenario independence are shown in Section 3.4. The SIC method allows the quantitative comparisons of system instantiations independent of scenario.

The method can be used in many areas. It can be applied to issues such as:

- Providing near real time analysis and results, and a mechanism for 'what if' situations.
- Providing a mechanism for the aggregation of estimates from subject matter advisers, from observations, or from general knowledge, especially in support of seminars or discussion groups.

³ The use of the term operational requirement in this document should not be confused with the use of this term in military operations. The usage here is more general, as will be seen by the definition given in Section 3.1.1.

- Guiding the analyst to the appropriate war game and extrapolating the results of the war game.
- The refinement and prediction aspects of the Battlelab process (Bowley and Lovasz 1999, and Bowley 1999). If the method is linked to the refinement issues, then the method should be linked to sensitivity analysis (an area of future work) to draw out key factors associated with the problem under study.
- A predictive method to help guide the next stage in the development of a problem under investigation. This can narrow the scope of interrogation for the problems. In the case of war games it can focus on the area for further investigation. This is especially relevant when big changes are experienced.

The method is flexible in its application in that it can be used in a variety of different circumstances and varying degrees of detail depending on the application required. It allows data to be reused, and like systems to be compared. Application of the method includes: providing a capability to view and define the system from a variety of different perspectives, and identification of critical aspects of the system. These aid the user in clearly defining the system and solving issues for a particular application. The method provides a powerful tool to describe and define a system for investigation and then compare different instantiations of the system.

When viewing or investigating a system it is important to identify what influences the system. Data to support defining the system comes from a variety of places. In order to define the system using the SIC method it is essential to do background research in terms of becoming familiar with the specific system of interest and issues which could influence it and its components. This can be done through interviews, reading documentation available about the system, and in some cases questionnaires could be used to get key attributes regarding the system, which are relevant to the study.

Three examples are provided in the following sections, illustrating the application of the method in highlighting the different components of the system:

- A biological system's ability to provide the required nutrients for its survival,
- A defence force considering a new capability purchase in the form of a new tank, and
- A control organisation looking at updating its standard operating procedures to become more efficient.

3.1 The System Model

The representation of the system shown in Figure 1 forms the basis of the comparison of the system instantiations. The model is composed of three central parts: the critical component, the system functions and the system enablers. The critical component and system functions are determined by the operational requirements of the system and are static from one instantiation to the next. These are considered as the frame of reference for comparisons between instantiations. The system enablers are the part of the system that

varies between different instantiations and define how the system functions operate on the critical components to achieve the operational requirements. Identifying the components and their definitions may be an iterative process and is critical to the successful application of the method in order to compare system instantiations. More detailed definitions of each part of the model along with illustrative examples are given in the following sections.

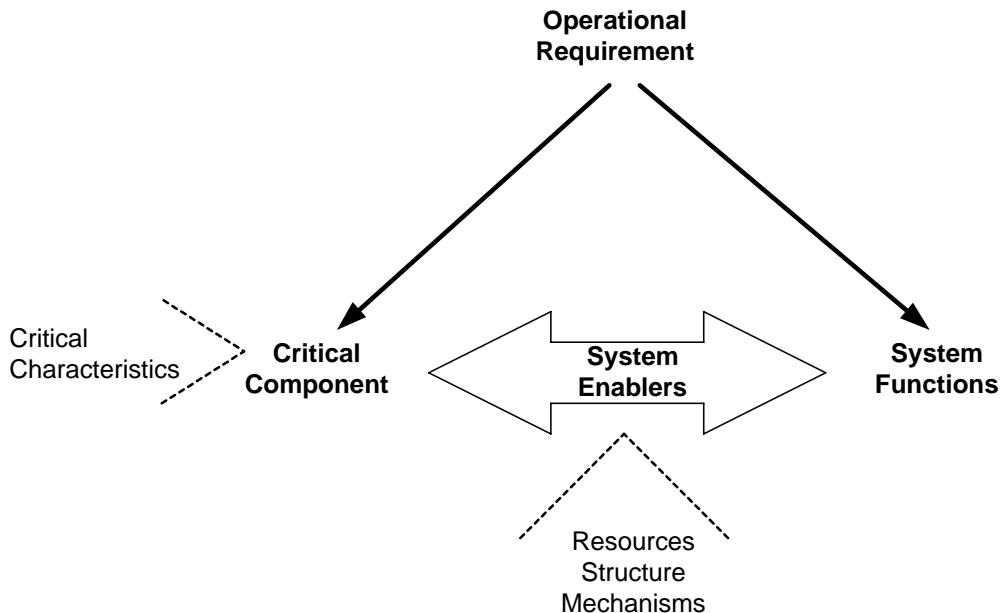


Figure 1: The System Representation

3.1.1 System's Operational Requirement

This method begins with the definition of the operational requirement of the system. Its selection greatly influences the definition of the other parts of the model as it defines the underlying purpose of the system.

The system's operational requirement defines the highest level goal of the system and sets the environment within which the system operates. It is generic and static in nature. Thus it is considered to be independent of any particular circumstance in which the system is placed. The operational requirement is governed by how the system works in its environment; of interest is what influence there is on the system, in particular the tempo with which the system is required to operate. A different system scenario does not necessarily change the overall aim of the system, nor the components within the system. The speed at which the system is required to react may affect the interaction of the components of the system, not what the components are. To determine the operational requirement of the system the analyst should answer the question 'how does the system as a whole attempt to influence the external environment⁴?' A possible tool for determining the system's operational requirement is the use of case tools (Larman 1998, and Lonsdale

⁴ External environment refers to everything outside of the system

2000b). Interview techniques and questionnaires are another option, as described in Anselm and Corbin (1990) and Minichiello et al (1991). The operational requirement is independent of scenario and defines the highest level goal of the system in terms of external influences on the system.

Examples of the selection of an operational requirement are as follows:

- In the biological system considered here, the operational requirement is nutritional survival.
- For the tank procurement example, the operational requirement could be considered to be the 'contribution of a capability to enhance a combined arms team in carrying out manoeuvre operations in the littoral environment'.
- The organisation example would have an operational requirement of 'providing advice and monitoring and controlling its subordinate organisations'.

3.1.2 Critical Component and Critical Characteristics

The critical component of the system, represented on the left side of Figure 1, is the essential 'thing' the system needs to achieve its operational requirement. It is static and generic in nature and is applicable throughout the whole system in the context of the system's operational requirement. Determination of the critical component is achieved by answering the question 'What is it that the whole system needs to meet the operational requirement?' Possible tools for determining the system's critical component include soft systems methods (Finegan 1994 and 2000). Another method is to use incident tracing techniques in a holistic manner, through the use of interview techniques (Minichiello et al 1991).

Examples of critical components are as follows:

- In the case of a biological system, with an operational requirement of nutritional survival, the critical component is defined as the blood, as blood is the part of the system that provides the delivery of nutrients and removal of waste. Blood alone does not ensure a biological system will reach its goal of surviving in the greater environment. However, it is the critical thing the system uses to ensure its nutritional survival.
- In selecting the right type of tank, the critical component is 'effect'. This is what the whole system needs to have to meet its operational requirement. The system, in this case the tanks, provides the contribution of 'effect' to 'enhance a combined arms team in carrying out manoeuvre operations in the littoral environment'.
- In the case of the organisation, the critical component is the 'information' that the organisation needs to undertake its operational requirement of providing advice, and monitoring and controlling its subordinate organisations.

Depending on the system in question, the method provides the ability to specify the key characteristics associated with the system's critical component, referred to as the system's

critical characteristics. The critical characteristics⁵ represent the attributes associated with the critical component in the operational requirements. The function decomposition techniques, see Universität Bremen (2000b), can be used to identify these characteristics. The number of characteristics and those chosen depends on the level of the study and what aspects are most important to the study. For more detailed studies there will be more characteristics listed than for a higher-level study. These critical characteristics are a list of the attributes that further refine the definition of the critical component and allow a more detailed assessment of the system.

Examples of critical characteristics are as follows:

- Consider once more a model of a biological system. In this system blood was defined as the critical component. Now the key characteristics of blood at the highest level would be red blood cells, white blood cells, proteins and water. However, a more detailed study may require these to be broken down further so that white blood cells were further divided into neutrophils, macrophages, lymphocytes and monocytes.
- In the example of the tank procurement, the critical characteristics that make up the 'effect' are identified as: fire power, protection, sustainment, and mobility. These are arrived at by not considering the outcome of the 'effect', but decomposing what capability is required to be achieved to meet the contribution of 'effect' to 'enhance a combined arms team in carrying out manoeuvre operations in the littoral environment'.
- In the case of the organisation with a critical component of 'information', the organisation views the information in a different manner. The attributes of the information are 'quality', 'timeliness' and 'accuracy'.

It is also important to remember that these characteristics are static in nature.

While some systems may have the same critical component, the critical characteristics may be different. For example, consider the case of an organisation with a critical component of 'information' and critical characteristics as described previously. Depending on the operational requirement, the same critical component may break down into different critical characteristics. An example of a different set of critical characteristics for 'information' could be 'type', 'format', 'transfer rate'. The critical characteristics depend on the operational requirement.

3.1.3 System Functions

The way in which the system utilises its critical component and/or the critical characteristics to meet its operational requirement is defined by the system functions, shown on the right side of Figure 1. These functions represent the activities undertaken by the system to achieve its operational requirement. They are static and generic in nature. These may be specific to given aspects of the system. The functions of the system are determined by answering the question 'how does the system use the critical component to

⁵ In the remainder of this document the critical characteristics are sometimes also simply referred to as characteristics, when it is clear what this means.

meet its operational requirement?' A possible tool for determining the system's functions is data flow modelling (Universität Bremen 2000a).

Examples of system functions are as follows:

- For the biological system being considered, the system functions could be defined as add nutrients, remove nutrients, add waste and remove waste. This sets the functions of the system at a very high level. The critical component level of abstraction required for the study determines the detail of the functions. For example, in a more detailed study, the function of add waste might become the two functions add carbon dioxide and add urea.
- For the case of the tank procurement, the functions of the system are identified as suppression, destruction, neutralisation, manoeuvre, canalise, and survive. These describe the interaction between the 'effect' and the contribution of this 'effect' to the operational requirement. So the system utilises its critical component of 'effect', that is, fire power, protection sustainment and mobility, to meet its operational requirement, 'enhancing a combined arms team in carrying out manoeuvre operations in the littoral environment', using the system functions of suppression, destruction, neutralisation, manoeuvre, canalise, and survive.
- Using the organisation system as an example, a more detailed breakdown of the functions is:
 - Assessment - consisting of gaining an understanding of the current situation
 - Monitoring - sourcing, storing, filtering, sharing and accessing information
 - Generation - develop products

As can be seen in the examples above, the system functions, as with the critical component, can be broken down into as much detail as is required for the study.

3.1.4 System Enablers

The system enablers, shown at the bottom centre of Figure 1, represent the variable or dynamic parts of the system as they change between instantiations. To determine the enablers of the system, the analyst should answer the question 'how does the system use the available 'equipment/resources' to allow the functions to utilise the critical component to meet the system's operational requirement?'. Knowledge-based system development (ARTI 2000), structured systems analysis and design methodology (Uni. of Glamorgan 2000 and Universität Bremen 2000c), activity modelling (Lonsdale 2000a and Universität Bremen 2000b) and computer aided manufacturing definition (US DoD 2000a and -b) are tools that can be used to help determine the system enablers.

An example of the selection of the enablers of the system can be seen by considering the case of the biological systems removal of non-gas waste from the blood via the kidney. The form that the kidney takes varies from one instantiation to the next. For example, in birds the kidney uses less water to extract waste than in a fish. So these two biological system instantiations have the same critical component and functions, but different system enablers.

It is recommended that the system enablers be further divided into three groups: resources, structure and mechanisms. In essence this division of the system enablers is arbitrary. The key requirement is to separate the system costs from the other enablers. Costs or resources are not included in the evaluation of the system, as they do not directly change how well a given system instantiation can achieve its goals⁶. It seems logical to group the other enablers into those relating to the physical layout of the system, the structure, and those relating to how the resources are used, the mechanisms. This reduces the time required when studying different system instantiations as the grouping of the system enablers provides a logical metric that can be associated with the change of the system. The system structure and mechanisms provide the systems functions with their ability to interact with the critical component and thus are shown in Figure 1 as the link between the system functions and critical component.

The system enablers can be considered in as little or as much detail as is required for the evaluation. The number of enablers can also vary. They can be further sub-divided to represent more detailed properties. These still need to be combined in some way to represent an overall estimate for each of the system enablers. For simplicity only high-level estimates of the enablers will be considered in the discussions in this document.

The simple analogy is used that the mechanisms are the tools used by the system, the resources are what the tools use, and the structure is the way you arrange the tools to transfer and gain access to the critical component. Examples in the following sections highlight particular mechanisms, resources and structure.

3.1.4.1 *Resources or System Cost*

The resources define the cost of a given system instantiation. Some examples of resources are; physical equipment, training, and manpower. The resources associated with a particular modification of the system provide the system cost.

Examples of resources are as follows:

- For the biological system, clearly such things as the organs, circulatory system and food are system resources, as would be the genetic coding required to use these systems.
- In considering the tanks; personnel, equipment, such as ammunition, weapon system, detection system, tracking system and self-protection system could be considered to be the resources.
- For the organisation: these could be considered to be the population of the system: communications links, computer equipment, software programmers, personnel, and data base maintenance.

⁶ This technique aims to populate the benefit side of a cost benefits analysis.

3.1.4.2 *Mechanisms*

The mechanisms define the system's ability to manipulate and interpret the critical component. Care must be taken in defining the mechanisms and the system functions, as these can sometimes be confused. As an aid to distinguishing between functions and mechanisms, a function must always have to be done, it is generic in nature. Conversely, the enabler mechanism is how you do the functions.

Examples of mechanisms of a system are:

- A mechanism of a biological system is the distribution of blood, that is, the pumping of the heart. Another mechanism may be the way osmosis is used to remove and add gasses to the blood. The key difference is that functions are enduring while mechanisms can change. For example there is always a need to add or remove gasses but the way it is done may vary between instantiations.
- In the case of the tank procurement, examples of 'mechanisms' would be training, doctrine, command and control, rules of engagement.
- In the organisation, there is always a need to store information, thus the storing of information is a function. However, the use of a given filing system is a mechanism as this is one way of achieving the function of storing information. Other mechanisms include templates, formats, data base management, standard operating procedures and references.

3.1.4.3 *Structure*

The structure is the way the resources are arranged and determines the ability of the system to transfer and gain access to the system critical component.

Examples of the selection of the structure of the system are:

- For the biological example, this would be the way the organs and circulatory systems are structured in a biological system.
- The tanks' 'structure' includes the layout of the tank itself, the equipment fits, and the distribution of the armour.
- The organisation 'structure' could include the manning distribution and layout.

3.1.5 Summary of Components

Table 1 provides a summary of the components identified in the method. The operational requirements for each system are:

- For the biological system; nutritional survival.
- For the tank procurement system; contribution of a capability to enhance a combined arms team in carrying out manoeuvre operations in the littoral environment.
- For the organisation; providing advice, and monitoring and controlling its subordinate organisations.

Table 1: Examples of the components of The System Instantiation Comparison Method

System	Critical component	Critical characteristics	System functions	System enablers		
				Resources	Mechanisms	Structure
Biological system	blood	red blood cells white blood cells - neutrophils - macrophages - lymphocytes - monocytes proteins	remove waste add waste - add CO ₂ - add urea remove nutrients add nutrients	organs genetic coding food circulatory system	distribution of blood osmosis	arrangement of organs circulatory system system structure
Tank procurement	effect	fire power protection sustainment mobility	suppression destruction neutralisation manoeuvre canalise survivability	personnel equipment weapons system detection system tracking system protection system	command and control rules of engagement training doctrine	layout of tank equipment fits distribution of armour
Organisation	information	quality timelines accuracy	assessment monitoring generation	population of system communication links computer equipment software programmers personnel data base maintenance	templates formats data base management system standard operating procedures references	layout manning distribution

Figures 2 to 4 provide a graphic summary of the three examples given. They focus on the definition of the systems and the components that make them up. Table 2 provides a summary of the steps and tools used to describe the system used for the SIC method.

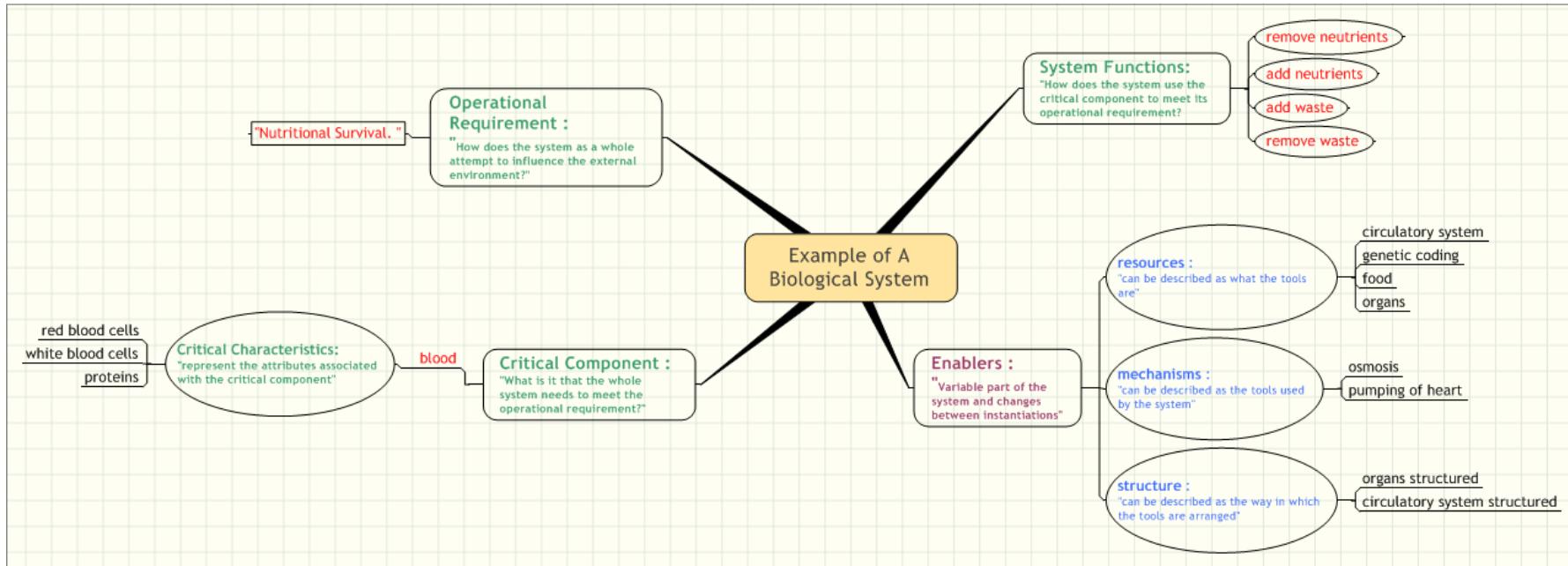


Figure 2: SIC Method: System Definition for the Example of a Biological System

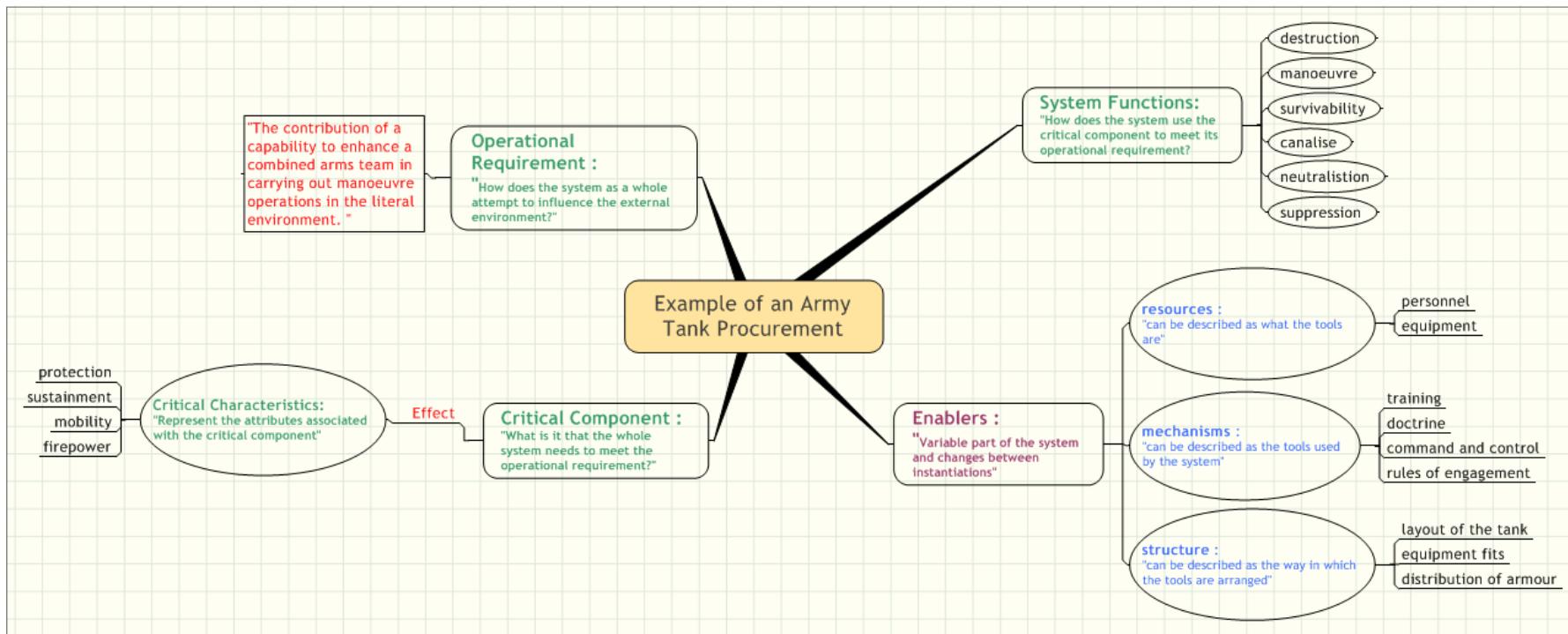


Figure 3: SIC Method: System Definition for the Example of an Army Tank Procurement

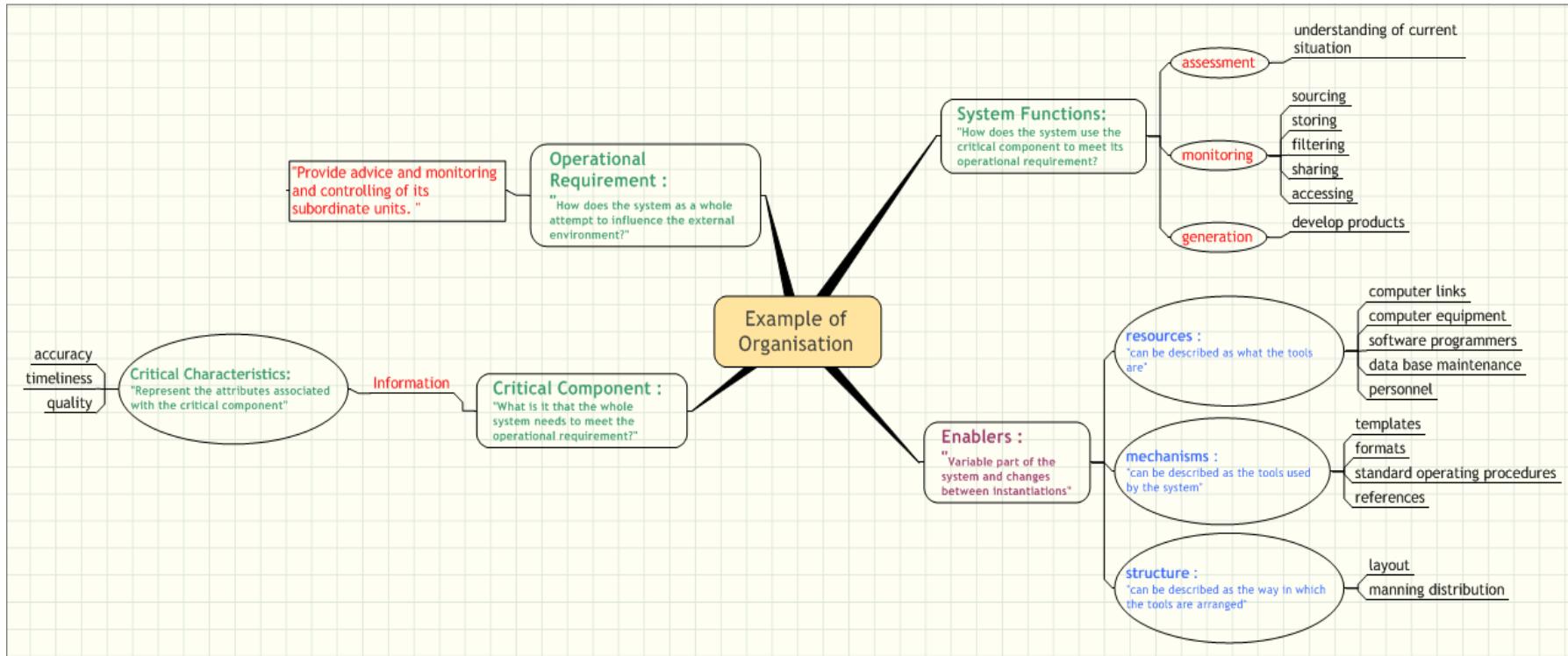


Figure 4: SIC Method: System Definition for the Example of an Organisation

Table 2: Summary of Tools for System Representation

Procedure	Steps	Possible Tools
Identify system components in terms of their generic and static nature	Identify operational requirement	Activity modelling, structured systems analysis and design, use case modelling, interview techniques
	Identify critical component	Soft systems, system dynamics modelling, interview techniques
	Identify critical characteristics	Activity modelling, functional decomposition, interview techniques
	Identify system functions	Data flow modelling, use case, functional decomposition, interview techniques
Determination of variable aspects of the system	Determine enablers	Soft Systems, interview techniques
	Mechanisms	Integrated DEFinition Language, interview techniques
	Structure	Knowledge based system development, interview techniques
Evaluation ^a	Determine weights	Decision analysis tools; analytical hierarchy process, multi criteria analysis
	Enabler values	Simulation, modelling, subject matter experts, war games, observation, interviews, operations research, decision support tools.

^a This aspect of the SIC method is discussed in following sections, but has been included here to provide a complete summary of tools.

3.2 Using the Method for Evaluation

Once the system model is defined the aim is to assess how 'well' the system enablers allow the system functions to utilise the critical component (characteristics) to achieve the operational requirement. The value that results from this assessment is referred to as the system measure.

The importance of a given critical characteristic may vary from function to function. We define this variation as the criticality index, which can be expressed in the form of weights. Examples of techniques for determining these weights include decision analysis tools (Goodwin and Wright 1952), such as decision trees (Marshall 1995), analytical hierarchy process (Goodwin and Wright 1952; and Saaty 1980), simple multi-attribute rating technique (Goodwin and Wright 1952), multi-attribute utility theory (Kadvany 2000), the data envelopment analysis method (Filar, Gaertner and Lu Wu in publication) and force field analysis (Vignaux 2000). These weights are fixed and do not vary between instantiations of the system; they are determined by the characteristics and functions, which are static. In the case of the biological system, a given characteristic of the blood may be more important to a given function, for example, in the function of add nutrient, red blood cells are of great importance as they hold oxygen, while white blood cells are of little importance as they do not carry any nutrients. Note that these weights can be used to calculate the overall system criticality of a characteristic. This value can be useful in determining which characteristic is most important to the system.

The importance of a system function to the overall system may also vary. Thus each function is also weighted. For the organisation example, the tempo of operation impacts on the system functions in terms of their weights.

An enabler measure is determined for each function in relation to each critical characteristic for a given system instantiation. The way of determining this measure will be system dependent and some possible techniques may include modelling (Coyle 1996; Bowden and Pearce 2000; Bowden, Gabrisch and Davies 1997; and Levis 1993), operations research techniques (Taha 1992; Gillett 1976; and Hiller and Lieberman 1973), simulation and war gaming (Bowley and Lovasz 1999), battle lab process (Bowley 1999), observations (Mills and Stothard 2000; and Rees and Kempt in publication), surveys (de Vaus 1995; and ABS 1993), interviews and qualitative techniques (Strauss and Corbin 1990; and Minchillo et al 1991), and decision support tools (Uni. Cambridge 2000). These measures are then combined taking into account the criticality of the system's critical characteristics for the given function and the importance of the function. This process is repeated for each instantiation. Once the initial study has been conducted, subsequent studies are easier, as the basic definition of the critical characteristics and system functions have been defined, and often the system enablers are also largely defined, reducing the initial overhead. Also, as part of the analyses, the system costs for different instantiations can also be determined from the resource system enablers.

The SIC method does not make any judgement on the quality of the system's outcome, only on the evaluation of the system's ability to support the generation of that outcome. In this way, a measure for evaluating the system can be obtained for a particular modification in terms of its system enablers. The key elements of a particular system are unique to that type of system.

3.3 Getting One Measure of the System

Table 3 provides a guide for collating and aggregating the data required to support the SIC method. In Table 3 values are given for each critical characteristic and system function pair. For function F1 these are listed in the table as the values A_i and B_i , where $i = 1$ to 3. Two values were used in this sample table to relate the two types of system enablers, SE1 and SE2, which impact on the system measure; structure and mechanisms. However, the number of measures is up to the analyst and this may vary from one to any number depending largely on the type and scope of the study. This information is the raw data that is used to determine the system measure. It is these numbers that will vary between instantiations. The value A_1 in Table 3 relates to how 'well' the instantiation currently being evaluated allows function 1 to utilise characteristic 1. In Table 3, two functions have been listed so values for the second function are also entered into the table; values C_i and D_i , where $i = 1$ to 3. Table 3 shows how all three variables; functions, critical characteristics and enablers, can be represented.

The characteristic weights (weight) are also given in the table. As stated earlier, these determine the criticality of the characteristics. The characteristic weights are given in the table as W_{FjCK} , where $j = 1$ to 2 and $k = 1$ to 3. Thus there is one weight for each critical characteristic/function pairing. These weights are used along with the data values A_i , B_i , C_i and D_i , $i = 1$ to 3, to determine the function characteristic measure. The way of combining these values is up to the analyst⁷. A very simple linear function is used in the headquarters example seen in Section 4, but any applicable function can be used, Anderson (2002); Bridgman (1922); de Neufville (1990); Fishburn (1967); Hwang and Yoon (1981); Williams, Bowden and Rees (2001); and Yoon and Hwang (1995) provide more examples of possible ways of combining values to form an overall value. The outcome of this combination is given in Table 3 as the values M_i , where $i = 1$ to 6.

The importance of each function, the function weight, is given in the table as W_{F1} and W_{F2} . These values are used to get an overall function measure, listed in the table as $FM1$ and $FM2$. The user is required to determine the function used to combine the function characteristic measures to get the overall function measure.

⁷ Some possible aggregation functions are given in Hesser (1991); and Williams, Rees and Bowden (2000).

Table 3: System Measure Determination

Function, Weight	Function 1, W_{F1}				Function 2, W_{F2}			
	Weight	SE1	SE2	Function Characteristic Measure	Weight	SE1	SE2	Function Characteristic Measure
Characteristic 1	W_{F1C1}	A1	B1	$M1 = F1(A1, B1, W_{F1C1})$	W_{F2C1}	C1	D1	$M4 = F4(C1, D1, W_{F2C1})$
Characteristic 2	W_{F1C2}	A2	B2	$M2 = F2(A2, B2, W_{F1C2})$	W_{F2C2}	C2	D2	$M5 = F5(C2, D2, W_{F2C2})$
Characteristic 3	W_{F1C3}	A3	B3	$M3 = F3(A3, B3, W_{F1C3})$	W_{F2C3}	C3	D3	$M6 = F6(C3, D3, W_{F2C})$
Function Measure				$FM1 = G1(M1, M2, M3, W_{F1})$				$FM2 = G2(M4, M5, M6, W_{F2})$
System Measure								$SM = H(FM1, FM2)$

The final manipulation relates to the calculation of the system measure (SM) in Table 3. This is achieved by combining the function measures⁸. Again the function used for this combination depends on the system being analysed. One issue that is hidden in this analysis is that of emergent behaviour and synergistic effects. These are reflected in two ways. First, in general because we are looking at the ability to carry out the required functions on the critical component using the system outcomes and not the output of the system these effects are already being considered. Second, the functions used to calculate the function characteristic measure, overall function measure and the overall system measure can be designed to allow for the impact of these issues. These functions can also be designed to ensure that the relationships between different system functions and critical characteristics are interdependent.

3.4 Relationship of Analysis to Context

One of the problems with many analysis techniques is that they are scenario dependent. This means that many evaluations need to be conducted to determine how well a system performs overall. One of the advantages of the method defined here is that the measure of the system is determined to enable it to have a broader application than any given scenario. Thus, a measure can be determined for a broad context⁹, which is set via the use of the operational requirement. This is because the measure is determined from the ability of the system to support the outcome and is not focused on evaluating the quality of the outcome, or the processes followed for a particular output. This means the actual activity in which the functions occur is less important, so the method is less sensitive to the specific scenarios.

The scenarios are accounted for in terms of the operational requirements of the system. The evaluations are conducted for instantiations within the same operational requirement. The method is particularly suited to investigating the introduction of new technology into a system and assessing its impact via comparison.

For example, in the case of the biological system four contexts can be defined: exerting activity, normal activity, resting and sleeping. Thus the context in this case depends on the nutritional requirements of the body to survive. So if the body were operating under stress there would be the need to supply more nutrients to the cells and remove more waste than when it is at rest. For the analysis of the biological system it is not important if the body is walking to a defined objective, just whether it is doing this under the contexts of exerting or normal activity.

The number of contexts that need to be considered depends on the variability in the function importance between each context. For example, in some biological systems it may

⁸ It is also possible to combine the values in such a way as to get an overall characteristic measure for the system if this is of interest. In this, the function characteristic measures are combined for each characteristic.

⁹ A context refers to a set of like scenarios that can be grouped together.

be necessary to define another context relating to hibernation. The context determines the rate at which the operational requirements needs are to be met.

The critical characteristic measures are independent of context, and so a change in context simply implies a change in function importance. Thus to determine the system measure for different contexts the analyst reassigns the weights on the system functions. The measures for each context can be combined using methods such as the technique for order preference by similarity to the ideal solutions method (Filar, Gaertner and Lu Wu in publication).

4. The Military Headquarters Model

The primary role of a military headquarters is to provide command and control to its subordinate elements, facilitated through the use of information, so that the whole military formation can operate in the most effective manner. As discussed in Grinde and Hesser (1990), information is a driver for the effective operation of a military headquarters. The commander uses information to make decisions that control the forces under them and to disseminate his/her intent. The speed of making a decision should not in itself be the ultimate goal of the headquarters. What is of more importance is the 'quality and timeliness' of decisions. Tied up in this issue is how you measure the quality of a decision. It is not sufficient to make a faster decision that is incorrect; it needs to be a quality decision in the appropriate timeframe. Thus a study of timeliness alone does not determine how well the overall system is operating.

To manage uncertainty related to the battlefield, information must have high fidelity, currency, consistency, sufficiency and be flexible in nature. The introduction of advanced information management systems can enhance the performance of command and control systems. Central to this performance is the capability to provide a common, coherent and accurate picture of the environment to the appropriate command elements.¹⁰

The way in which a military headquarters manages and utilises its information, in particular with the introduction of information technology, offers the potential to provide an operational edge for the decision processes and ultimately the whole system. It is assumed that future command and control environments will be drastically changed by the introduction of new technologies and the information age. However, these technology advancements by themselves do not necessarily relate to an increase in military effectiveness; the technology must be employed within a suitable training regime, organisational structures and concepts of operations.

¹⁰ These concepts are an extension of the work presented in Grinde and Hesser (1990) and Nobel and Wheatley (1999).

There is a requirement to determine the impact of the introduction of new technology into a military headquarters environment. The SIC method is a method that can be used to achieve this.

4.1 Defining the SIC Method Components as Applied to a Military Headquarters

The SIC method was developed through a requirement to provide a simple, flexible and cost-effective approach on which to base evaluations of command and control systems. Therefore, it seems appropriate to use a military headquarters, the centre for command and control, as a typical example with which to illustrate its application.

A military headquarters epitomises the concept of a complex pluralist system, as defined in Flood and Jackson (1991). Introducing new technologies adds further complexity, resulting in changes to the processes and cultural aspects of the headquarters. It therefore poses a challenge for evaluation in terms of generically defining the headquarters as a system, and providing a flexible and cost-effective method to conduct comparisons between instantiations.

The critical component of a military headquarters is information. In understanding the information requirements of a headquarters it is necessary to break the critical component into critical characteristics. These represent the key information requirements to perform the headquarters' functions. The critical characteristics are the generic set of the commander's critical information requirements. As supported by NATO 1998; Australian Army (1996); Gridne and Hesser (1990), Hesser (1991); Lane and Galvin (1999); Lloyd Merfun (1998); Nobel and Wheatley (1999) and collected military exercise data, they are applicable across all scenarios and can be extracted from the standard messages received, transmitted and used by a headquarters. It is proposed that this data is all that is needed to make decisions within the headquarters and all data that flows into, out of and within the headquarters fits into one of these categories. These categories are generic in nature and independent of level of command, and essentially define the data required to obtain situational understanding in the battlespace. The authors have determined that for a military headquarters, critical characteristics are (listed in no particular order):

- Own: identity, location, status and intent
- Opposition: identity, location, status and intent
- Neutral: identity, location, status and intent
- Geospatial
- Environment (including weather)

Key activities undertaken on the information by the system to achieve its operational outcomes are defined as the system functions. The focus of these functions is towards monitoring, understanding and trying to control the environment the headquarters is immersed in. Once the environment is understood, informed assessments can be made.

This then forms the generic basis for defining the functions associated with headquarters' operations¹¹. These functions provide the required information to the decision maker and the command and control processes that enable assessment, planning and execution, thus defining the system functions.

For a military command and control system, such as a military headquarters¹², the system enablers associated with resources, structure and mechanisms provide a representation of how well the system manages the information, i.e., its ability to interpret, manipulate, access and communicate information internally within the sub-system and between systems.

Figure 5 provides a summary of the components associated with the technique for the evaluation of a military headquarters.

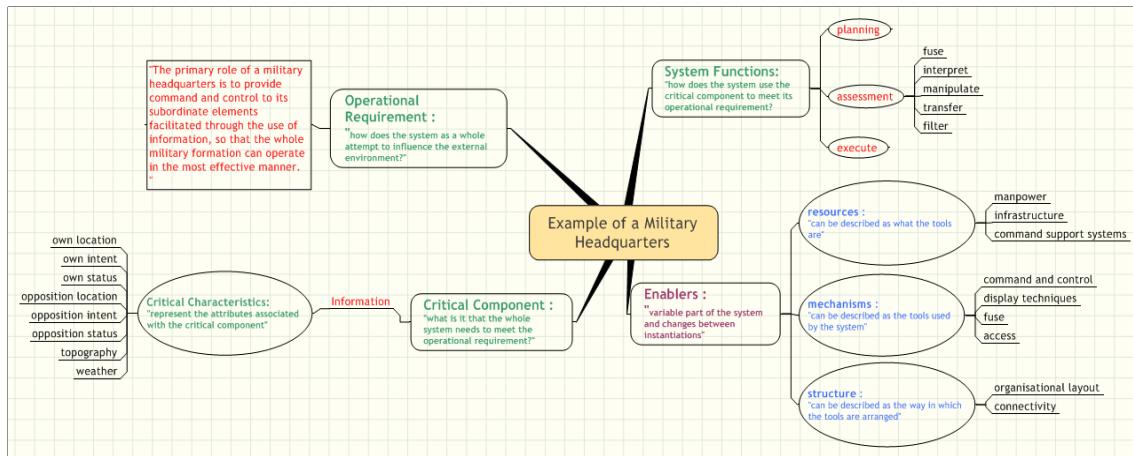


Figure 5: Example of a Military Headquarters Representation

In any military system there are considered to be three different tempos of operations: high, medium and low. These define the demands on a military headquarters. Thus the three contexts for a military system are defined as high, medium and low tempo.

¹¹ The generic nature of the functions of a command and control system, regardless of the technology or the doctrine is supported by Grinde and Hesser (1990) and Kirzl (1999). The functions associated with command and control are discussed further in Checkland (1993); Kearney (1998); and Bowden and Davies (1998).

¹² While both the example of organisation discussed in Section 3.1, and the military headquarters, have been defined as having the same critical component, due to their different operational requirements they have different critical characteristics.

4.2 Application of the Method to the Evaluation of a Military Headquarters

To show how the method works, three instantiations of a system are compared. The first instantiation is considered as the base instantiation, the second is a slight enhancement to one component of the system, and the third provides an enhancement to the system as a whole. What will be investigated is the impact of enhancing the information on friendly locations in a headquarters at brigade level. In the second instantiation the change is in the form of regular automated updates of own positions. Instead of receiving own locations every two hours, friendly locations will be automatically sent every 10 minutes from a global positioning system attached to each of the sub-units. These locations are then manually added to the battle map. In the third instantiation this data will be automatically placed on a digital battle map. Thus the overall effect of both instantiations is more regular and accurate information about own forces locations.

For the example considered here, the neutral force, identity and weather information are not considered to be significant for illustrative purposes, so these critical characteristics do not need to be included in the analysis.

For the changes being considered in the example, the functions planning, execution and assessment are assumed to be the most affected. This will help to simplify the explanation of the method. Note that in the planning and assessment functions, the information elements are transferred and accessed internal to the headquarters, while the execution function is the ability to access and transfer information external to the headquarters. Representative values are used to illustrate the method.

The variations in the system instantiations considered in this example result in changes in all three enablers; resources, structure and mechanisms. For example, the second instantiation introduces global positioning system resources to lower units so their position information can be passed to the headquarters. The third instantiation introduces further computing power into the headquarters to process and display the extra location data.

Table 4 provides the results of collating and analysing the data for the first instantiation required to support the method. Values are given for each of the information characteristics, described on the left hand side of the table, and the system function, given across the top of the table. For each function, using the planning function as an example, two values are used to relate the types of system enablers, E1 (structure) and E2 (mechanism), which impact on the system measure. This value relates to how 'well' the instantiation currently being evaluated allows the functions to utilise a specific information characteristic. It is these numbers that vary between instantiations. There are many ways of determining these values, as discussed in Section 3.2

The critical characteristic weights are also given in the table as weights. These determine the criticality of the characteristics to the given functions. Thus there is one weight for each

critical characteristic function pairing. For a headquarters, the critical characteristic weights can be determined using a criticality index as done in Hesser (1991). This allows for the calculation of the weights using each characteristic's perishability, frequency and importance. An alternative technique would be to use the analytic hierarchy process (Saaty 1980), allowing subject matter experts to rank the critical characteristics for each function. Yet another possibility is the use of data envelopment analysis (Boussofiane, Dyson & Thanassoulis 1991); this will be explored further in Section 4.2.3.

Table 4: Evaluation For The First Instantiation

Function Weight	FUNCTIONS											
	Planning				Assessment				Execute			
Information Characteristics	Weight	E1	E2	Weighted Function Measure	Weight	E1	E2	Weighted Function Measure	Weight	E1	E2	Weighted Function Measure
Opposition Location	0.8	0.5	0.5	0.16	1	0.5	0.5	0.6	0.8	0.5	0.5	0.8
Opposition Status	0.5	0.5	0.5	0.1	0.6	0.5	0.5	0.36	0.7	0.5	0.5	0.7
Opposition Intent	0.7	0.5	0.5	0.14	0.7	0.5	0.5	0.42	0.7	0.5	0.5	0.7
Own Location	0.8	0.5	0.5	0.16	0.9	0.5	0.5	0.54	1	0.5	0.5	1
Own Status	0.6	0.5	0.5	0.12	0.6	0.5	0.5	0.36	0.4	0.5	0.5	0.4
Own Intent	0.9	0.5	0.5	0.18	0.4	0.5	0.5	0.24	0.4	0.5	0.5	0.4
Geospatial	0.8	0.5	0.5	0.16	0.3	0.5	0.5	0.18	0.8	0.5	0.5	0.8
Cross Characteristic Function Measure				1.0					2.7			
System Measure	8.5											

These weights are used, along with the system enabler values, to determine the function characteristic measure. The way of combining these values is up to the analyst and depends on the system being studied. A simple weighted sum is used in this example.

The final element of the evaluation is the function weights. These weights determine the criticality of the functions to the system. Again, the analytic hierarchy process could be used to calculate these weights. Another technique would be to gather data relating to the length, frequency and importance of each function to the headquarters.

The function weights and the function characteristic measures are then combined to provide the system measure. Again the function used to combine these values is up to the

analyst and depends on the system being studied. Once more in this example a weighted sum is used. Table 4 shows the evaluation for the first instantiation (the base line case).

For the second instantiation, the introduction of the proposed changes in the system can be described as follows. There is a substantial change in the transfer of external information into and out of the headquarters. This increase in information transfer is accompanied by an increase in communications bandwidth usage. The ability to access this information is hampered because procedures are not in place to accommodate such a large volume of information. The fusion of this information has also not been addressed in this instantiation. Once the information is internal to the headquarters, its transfer is also hindered due to the increased volume. The impact of these changes is reflected in the bold values in Table 5.

Table 5: Evaluation for the Second Instantiation

	FUNCTIONS											
	Planning			Assessment			Execute					
Function Weight	0.2			0.6			1					
Information Characteristics	Weight	E1	E2	Weighted Function Measure	Weight	E1	E2	Weighted Function Measure	Weight	E1	E2	Weighted Function Measure
Opposition Location	0.8	0.4	0.4	0.128	1	0.6	0.4	0.6	0.8	0.5	0.5	0.8
Opposition Status	0.5	0.5	0.5	0.1	0.6	0.5	0.5	0.36	0.7	0.5	0.5	0.7
Opposition Intent	0.7	0.5	0.5	0.14	0.7	0.5	0.5	0.42	0.7	0.5	0.5	0.7
Own Location	0.8	0.3	0.3	0.096	0.9	0.4	0.3	0.378	1	0.4	0.4	0.8
Own Status	0.6	0.5	0.5	0.12	0.6	0.5	0.5	0.36	0.4	0.5	0.5	0.4
Own Intent	0.9	0.5	0.5	0.18	0.4	0.5	0.5	0.24	0.4	0.5	0.5	0.4
Geospatial	0.8	0.5	0.5	0.16	0.3	0.5	0.5	0.18	0.8	0.5	0.5	0.8
Cross Characteristic Function Measure	0.9			2.5			4.6					
System Measure	8.1											

The changes described above are determined using the most appropriate method available. These could include qualitative and quantitative observation, modelling and simulation of parts of the system as described in Section 3.2.

For the third instantiation, the introduction of the proposed changes in the system can be described as follows. There is a large change in the transfer of external information into

and out of the headquarters. This increase in the volume of information transferred is accompanied by an increase in communications bandwidth. The ability for the whole system to manage this information has also been accommodated, via the use of an automated command support system within the headquarters to facilitate the transfer, interrogation and manipulation of information elements associated with the system. Table 6 shows the evaluation of the 3rd instantiation. Once more, the values that vary from the baseline are in bold.

Table 6: Evaluation for the Third Instantiation

Function Weight	FUNCTIONS											
	Planning				Assessment				Execute			
	0.2			0.6			1					
Information Characteristics	Weight	E1	E2	Weighted Function Measure	Weight	E1	E2	Weighted Function Measure	Weight	E1	E2	Weighted Function Measure
Opposition Location	0.8	0.6	0.7	0.21	1	0.5	0.6	0.66	0.8	0.8	0.7	1.20
Opposition Status	0.5	0.5	0.5	0.10	0.6	0.5	0.5	0.36	0.7	0.5	0.5	0.70
Opposition Intent	0.7	0.5	0.5	0.14	0.7	0.5	0.5	0.42	0.7	0.5	0.5	0.70
Own Location	0.8	0.8	0.7	0.24	0.9	0.7	0.9	0.86	1	0.9	0.9	1.80
Own Status	0.6	0.5	0.5	0.12	0.6	0.5	0.5	0.36	0.4	0.5	0.5	0.40
Own Intent	0.9	0.5	0.5	0.18	0.4	0.5	0.5	0.24	0.4	0.5	0.5	0.40
Geospatial	0.8	0.5	0.5	0.16	0.3	0.5	0.5	0.18	0.8	0.5	0.5	0.80
Cross Characteristic Function Measure				1.1				3.1				6.0
System Measure	10.2											

Table 7 provides the overall comparison of the three system instantiations. The second column gives the system measure, that is, the measure of how 'well' the given instantiation allows the system to perform its functions on the information. A larger number in this column indicates that the system instantiation is better. The third column gives a percentage change from the baseline instantiation. This analysis shows that just increasing the bandwidth and providing own location more regularly does not increase the effectiveness of the system as a whole. However, incorporating this change into the whole system via the management of the information elements does increase the system effectiveness.

Table 7: Comparison of System Instantiations

Instantiation	System Measure	Change
1	8.5	-
2	8.1	Insignificant
3	10.2	Moderate

This analysis defines the change in system effectiveness for a single context. The next step in the analysis is to carry out an analysis of the system over all defined contexts.

4.2.1 Ranking the Overall System Contexts

Table 4, Table 5 and Table 6 illustrate how well the system has performed through the system measure, which can be equated to how effective the functions are performing in the headquarters for a particular instantiation. In order to rate the instantiations, Table 8 represents a more detailed study incorporating the system context.

To achieve the overall system evaluation the technique for order preference by similarity to ideal solution methodology is applied(Filar, Gaertner & Lu Wu in publication). This effectively ranks the overall systems in order to maximise them against the headquarters functions.¹³

It is important to note that the examples provided are shown in three dimensions, however, any number of dimensions can be adopted. The dimension of the example would depend on the number of contexts being considered.

In the technique for order preference by similarity to ideal solution, the main criterion for the evaluation needs to be defined. In this case the contexts of the system are defined by the operational tempo: low, medium and high have been used in this case¹⁴. To illustrate the concept it is assumed that the data calculated so far has been for medium operations. Random data will be used for low and high tempo operations and for instantiations 4 to 6 for medium tempo operations. This is illustrated in Table 8. The system measures, given in columns two, three and four of Table 8, provide a summary of the calculated system measures for each context. Also included in this table are the maximum solution and minimum solution. The maximum and minimum solutions are the best and worst possible instantiations. In this case they are taken as the maximum and minimum values for the six instantiations, however, this is not always the case. The maximum and minimum values

¹³ This is one method of ranking solutions. An alternative is presented in the next section where it is used to rank the information characteristics. If a single optimal solution is to be found then game theory(Binmore 1992) can be used. However, this approach is not of interest here as it is the role of DSTO to advise on the value of solutions, not to pick one.

¹⁴ The number of contexts is analysis dependent and will be influenced by the sensitivity of the measures to the different contexts. The more sensitive the measures, the greater the number of contexts required.

may in fact be an instantiation that does not actually exist. For example, the minimum value may be based on the minimum acceptable value of the system.

Table 8: System Instantiation Measures In Relation To Context

System Instantiation	Low Tempo	Medium Tempo	High Tempo
1	7.61	8.50	9.18
2	9.41	8.10	7.78
3	9.33	10.20	10.66
4	8.91	9.30	11.26
5	9.27	10.67	11.49
6	9.74	9.78	10.17
Maximum	9.74	10.67	11.49
Minimum	7.61	8.25	7.78

In order to look at the overall operational capability, each context is weighted in accordance with the importance of its overall capability. For this example it is assumed that context 1 represents a low tempo of operation and is weighted as 0.25, context 2 represents a medium tempo of operation and is weighted as 0.5, and context 3, the high tempo, is weighted as 1.0. In reality, weighting of contexts may depend on factors such as the likelihood of the context occurring and the criticality of the system in the given contexts.

Having determined the weights of the contexts, the instantiations can be ranked using the technique for order preference by similarity to ideal solution (Filar, Gaertner & Lu Wu in publication). This determines the ratio of the distance that a given instantiation is from the maximum solution in comparison to the distance it is from the minimum solution. The ratios for the values in Table 8 are given in Table 9. The closer the ratio is to zero the closer the system is to the maximum solution. Thus, in this example the instantiation that is closest to the ideal is instantiation 5 and the instantiation closest to the negative ideal solution is instantiation 2.

Table 9: Instantiation Ranking in Relation to Maximum and Minimum Instantiations

Instantiation	Ratio
1	0.65
2	0.88
3	0.21
4	0.18
5	0.03
6	0.33

4.2.2 System Cost

Generally the next step considered is the cost of each system. Due to the way the system was defined this is given by system resources. Thus for the above example the changes in cost would be the inclusion of such resources as GPS systems for lower level units and changes in staff due to automation of some work in the headquarters. This will not be considered in this document, but is the focus of future work. Ultimately the SIC method can be used to assist in a cost-benefit trade off analysis. Thus the question of what instantiation of the system is most cost-effective can be addressed.

4.2.3 Calculation of Criticality of Information Characteristics

As described in Section 3.3, it is possible to determine the overall system criticality for each of the critical characteristics. This data provides an indication of the relative importance of the different characteristics of information to the headquarters as a whole. As mentioned earlier, there are numerous ways of doing this including the analytical hierarchy process (Saaty 1980), regression equations (Hesser 1991) and data envelopment analysis (Boussofiane, Dyson & Thanassoulis 1991). In this section the data envelopment analysis method is discussed in detail. All three methods are discussed in more detail in Williams, Rees and Bowden (2000).

Consider the use of two measures in the calculation of the information characteristic criticality¹⁵. The first step in defining the characteristic criticality is to define the critical boundary. The standard process for defining the critical boundary, is based on linear programming and is given in Boussofiane, Dyson and Thanassoulis (1991). Next, two lengths are calculated for each information characteristic. The first of these is the vector length from the origin to each point, defined here as D1. Consider now the vector from the origin to the boundary, which passes through the point being considered, this length is D2. The criticality index is then the ratio of the original vector length (D1) to the extended vector length (D2). Thus the criticality gives a ratio reflecting how far the point is from the critical boundary.

There are several problems with using linear programming to define the optimal boundary. The use of linear programming to define the optimal boundary means that it and the intersection on the boundary are hard to calculate. Also there is a problem with the ratios generated. That is, it is possible to get points on or very near the boundary that are actually far from optimal. Ideally the only solution that gives a ratio of one should be the point that takes the maximum possible value in all measures. To help overcome these issues, instead of using linear programming to define the boundary a simple circle with following equation is proposed by the authors:

$$y^2 + x^2 = (x_{\max})^2 + (y_{\max})^2,$$

where x_{\max} and y_{\max} are the maximum values that measures x and y can take.

¹⁵ Two measures have been used for clarity of explanation, however, the formulae for n measures is given later.

This means that for the solution (a, b) , $D1$ is given by

$$D1(a, b) = \sqrt{a^2 + b^2}.$$

Also, for all the points, $D2$ is given by

$$D2(a, b) = \sqrt{(x_{\max})^2 + (y_{\max})^2}.$$

So the ratio will be given by

$$\rho = \frac{D1(a, b)}{D2(a, b)} = \frac{\sqrt{a^2 + b^2}}{\sqrt{(x_{\max})^2 + (y_{\max})^2}}.$$

Figure 6 shows a plot of the ratio when the boundary is defined by a circle and where x_{\max} and y_{\max} equal four. Figure 6 shows that there is a favouring of solutions near the axis. For example, the solution of $(4, 0)$ is considered a better solution than $(3, 2)$. This is a direct result of the nature of the Euclidean distance and a concave hull. In fact the use of linear programming actually creates a tighter boundary, emphasising this characteristic further.

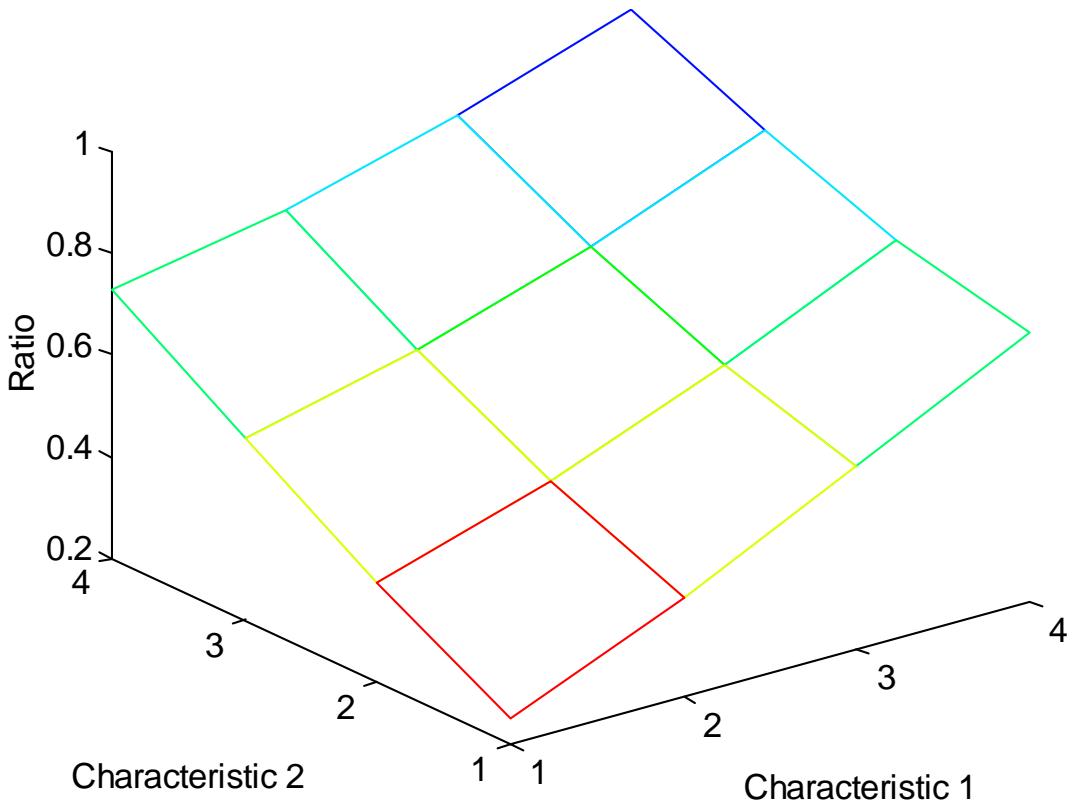


Figure 6: Ratio for a Circular Optimal Boundary

As an alternative, consider a boundary defined by the hyperbola

$$y = \frac{x_{\max} \times y_{\max}}{x}. \quad (\text{Eqn 1})$$

In this case, to calculate D2 we must first determine where the extension of the point (a, b) intersects with the hyperbola. The equation of the line going through the origin and the point (a, b) is given by

$$y = \frac{b}{a} x. \quad (\text{Eqn 2})$$

Solving simultaneously equation (1) and equation (2) gives the intersect point as being

$$\left(\sqrt{\frac{a(x_{\max} \times y_{\max})}{b}}, \sqrt{\frac{b(x_{\max} \times y_{\max})}{a}} \right).$$

Thus

$$\begin{aligned} D2(a, b) &= \sqrt{\frac{a(x_{\max} \times y_{\max})}{b} + \frac{b(x_{\max} \times y_{\max})}{a}} \\ &= \sqrt{\frac{(x_{\max} \times y_{\max})}{a \times b} (a^2 + b^2)} . \end{aligned}$$

Therefore,

$$\begin{aligned} \rho &= \frac{\sqrt{(a^2 + b^2)}}{\sqrt{\frac{(x_{\max} \times y_{\max})}{a \times b} (a^2 + b^2)}} \\ &= \sqrt{\frac{a \times b}{(x_{\max} \times y_{\max})}} . \end{aligned}$$

This type of function tends to favour points towards the centre, as shown in Figure 7 for $x_{\max} = y_{\max} = 4$.

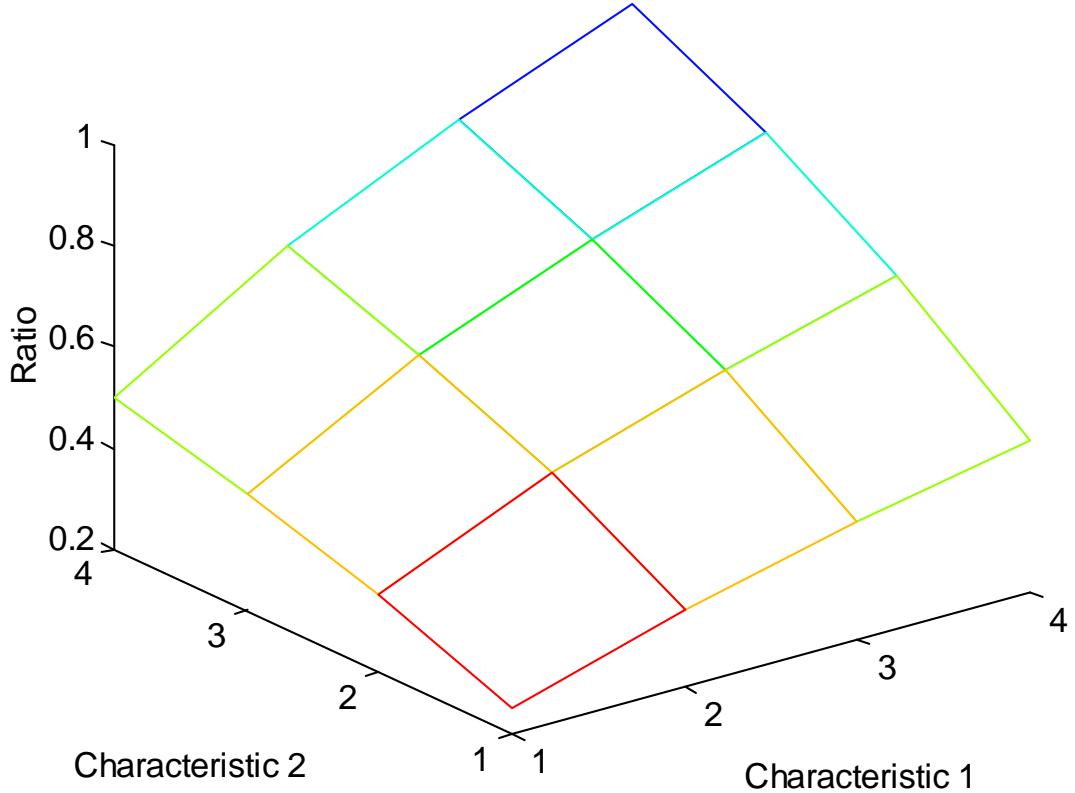


Figure 7: Ratio for a Hyperbola Optimal Boundary

A third case is considered. It is this alternative that is currently considered to be the method of choice for determining the criticality of information characteristics and more generally for determining the criticality of the system characteristics. This involves the use of a line with gradient minus one and going through the point (x_{\max}, y_{\max}) . This line has the equation

$$y + x = x_{\max} + y_{\max}. \quad (\text{Eqn 3})$$

The intersection of equation (2) and (3), is given by

$$\left(\frac{a(x_{\max} + y_{\max})}{a+b}, \frac{b(x_{\max} + y_{\max})}{a+b} \right).$$

Thus

$$D2(a, b) = \frac{\sqrt{a^2 + b^2} (x_{\max} + y_{\max})}{a+b},$$

which gives

$$\rho = \frac{a+b}{x_{\max} + y_{\max}}.$$

Figure 8 shows that this boundary gives a more linear solution to the problem, which favours neither the edges nor the centre.

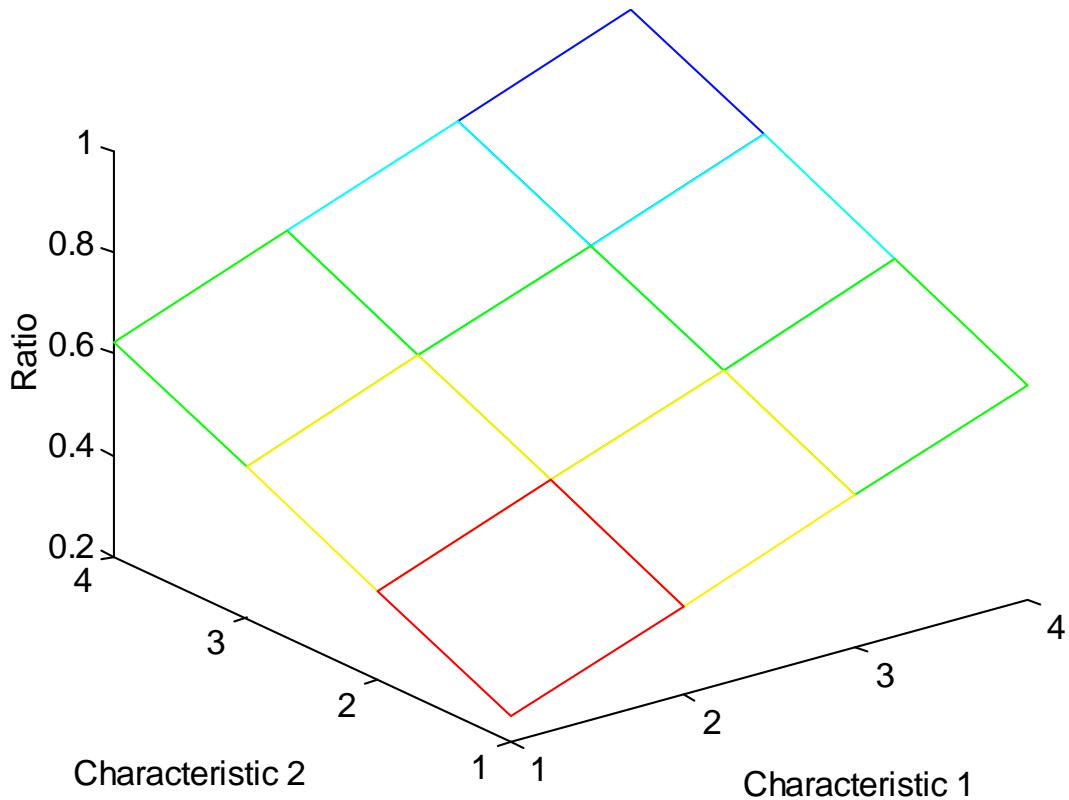


Figure 8: Ratio for a Linear Optimal Boundary

The line boundary is extended to allow for n measures. In n -dimensions this boundary has the equation

$$\sum_{i=1}^n x_i = \sum_{i=1}^n x_{\max i} .$$

Consider the point defined by $A = (a_1, a_2, \dots, a_n)$ that represents the measures of an information type where n measures are considered. The distance from the origin to this point is given by

$$D1(A) = \sqrt{\sum_{i=1}^n a_i^2} .$$

The parameterised representation of the line going through the point A and the origin is

$$X(t) = (a_1 t, a_2 t, \dots, a_n t) .$$

To determine where this line intersects the optimal boundary, the parameterised line is substituted into the equation of the boundary giving

$$\sum_{i=1}^n a_i t = \sum_{i=1}^n x_{\max i} .$$

So the value of t is

$$t = \frac{\sum_{i=1}^n x_{\max i}}{\sum_{i=1}^n a_i} .$$

This gives the point where this line intersects the optimal boundary as

$$I = \left(\frac{a_1 \sum_{i=1}^n x_{\max i}}{\sum_{i=1}^n a_i}, \frac{a_2 \sum_{i=1}^n x_{\max i}}{\sum_{i=1}^n a_i}, \dots, \frac{a_n \sum_{i=1}^n x_{\max i}}{\sum_{i=1}^n a_i} \right).$$

So

$$D2(A) = \sqrt{\sum_{i=1}^n a_i^2} \frac{\sum_{i=1}^n x_{\max i}}{\sum_{i=1}^n a_i} ,$$

therefore

$$\rho = \frac{\sum_{i=1}^n a_i}{\sum_{i=1}^n x_{\max i}} .$$

The actual form that the optimal boundary takes depends on the study. This choice is left to the analyst but above examples of possible boundaries can be used as a guide. In Yoon and Hwang (1995) a general form of different optimal boundaries is considered.

The criticality index for each of the information characteristics can be achieved by using its importance, frequency and perishability (Hesser 1991). An artificial sample set of data is shown with a rating out of 5¹⁶ in Table 10.

¹⁶ So $\max_x = \max_y = 5$.

Table 10: *Perishability, Frequency and Importance for Information Characteristics*

Information Characteristic	Importance			Perishability			Frequency		
	Planning	Monitoring	Execution	Planning	Monitoring	Execution	Planning	Monitoring	Execution
Friendly - position	1	2	2	2	2	4	1	3	5
- status	4	4	4	3	3	3	1	1	1
- intent	5	2	3	1	1	1	1	1	1
Enemy - position	3	5	5	1	1	1	1	1	1
- status	3	4	4	5	5	2	1	4	4
- intent	5	7	7	3	3	1	1	1	1
Neutral - position	3	4	4	5	5	2	1	4	4
- status	1	2	2	2	2	2	1	1	1
- intent	1	3	2	1	1	1	1	1	1
Topography	4	1	1	1	1	1	1	1	1
Weather	2	2	2	1	1	1	1	1	1

The data is then combined using the data envelopment analysis method as defined above. This gives the criticality values shown in Table 11 and Figure 9. This was achieved using the three measures of perishability, frequency and importance, thus $n = 3$, for each of the functions and information characteristics.

Table 11: *Criticality Value for Each Information Category*

	Planning	Monitoring	Execution
Friendly - position	0.16	0.28	0.44
- status	0.32	0.32	0.32
- intent	0.28	0.16	0.20
Enemy - position	0.20	0.28	0.28
- status	0.20	0.24	0.24
- intent	0.36	0.36	0.28
Neutral - position	0.36	0.52	0.40
- status	0.16	0.20	0.20
- intent	0.12	0.20	0.16
Topography	0.24	0.12	0.12
Weather	0.16	0.16	0.16

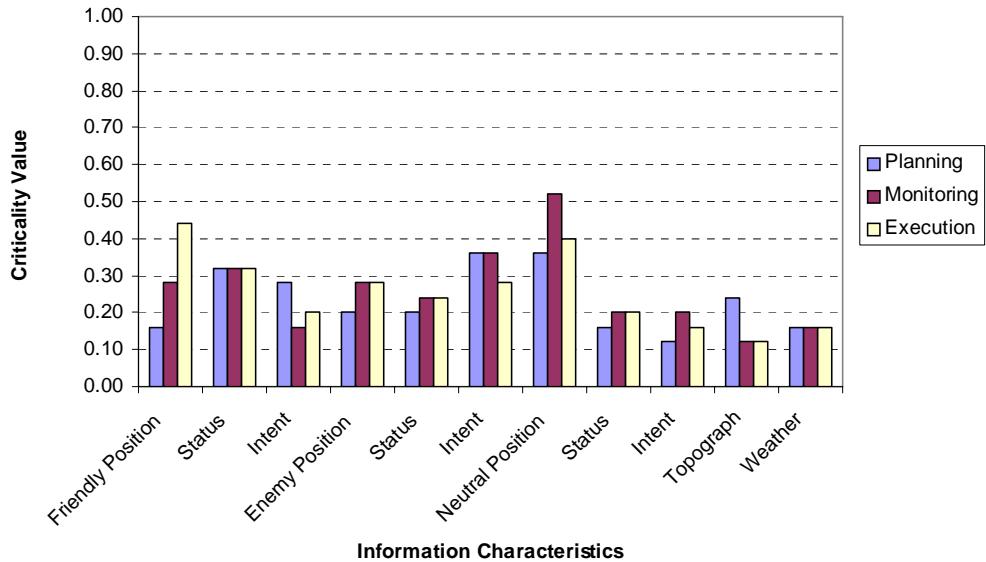


Figure 9: Plot of Criticality Values Versus Information Characteristics

5. Discussion and Conclusions

This document delineates the definition, analysis, and evaluation of a complex system by developing a method that allows quantitative comparative estimates of system instantiations to be made, and allows for the calculation of criticality values associated with the main components of the system.

The SIC method models the system as three parts: system critical component, system functions and system enablers. Two of these, the system critical component and system functions, represent the system operational requirements and are fixed for each system instantiation. The system enablers provide the capability of the system to support these requirements and are variable in nature. Thus in comparing different system instantiations it is only the enablers that change; the remainder of the model is fixed. Thus the system measure is the dependent variable given by the independent variables, namely, system critical component, functions and enablers.

In terms of systems of systems methodologies, the SIC method is aimed at use with complex pluralist systems, although it is also applicable to both complex unitary and complex coercive systems (Flood & Jackson 1991). The advantage of this method is the way it views the system from the aspect of how well the system enablers allow the system's functions to use the critical components to achieve its operational requirements. Other methods of evaluation focus on the quality of the outputs of the system or on process oriented approaches.

The SIC method does not make any judgement about the quality of the system's outcome, only an the evaluation of the system's ability to support the generation of that outcome. In this way, a measure for evaluating the system can be obtained for a particular modification in terms of its system enablers. The key elements of a particular system are unique to that type of system.

The SIC method is especially relevant when big changes are experienced, and well suited to real time analysis and results for 'what if situations'; providing a predictive aspect to help narrow and scope interrogation of problems. This method has the advantages of being:

- Simple;
- Flexible;
- Scalable;
- Defined by a generic representation of the system;
- Widely applicable; and
- Scenario independent.

A military command and control system was used as an example for the application of the method. Generic characteristics associated with the information and the functions used by a military headquarters were used as the basis to represent the components of the system. System measures associated with different instantiations were obtained and rated using a number of different techniques. This analysis incorporated the context of the system through the system functions. The criticality of the information for headquarters operations was also calculated, and ranked using the development of a new approach, which is considered useful for focussing the introduction of information technologies. This is of particular importance for the design of combat support systems in terms of issues related to information degradation and priority of information transfer and display.

The method has been used in a number of real applications. The application of the method was particularly beneficial for defining the system, and providing a focus for evaluation. Two examples are: the evaluation of intelligences, surveillance and reconnaissance systems in East Timor, and investigations into interoperability between American, British, Canadian and Australian armies within a coalition force.

For the case of the intelligence, surveillance and reconnaissance investigation, information was used as the critical component. The method implemented was similar to the examples of the military headquarters. New technology was introduced into the system and instantiations measures were taken. The method also allowed a holistic view of the system.

For the coalition army activity, interoperability was used as the critical component with factors associated with interoperability used as the critical characteristics. In this case the method was used primarily to define the system holistically for investigation.

There are two areas planned for future work on the SIC method. The first relates to the linking of the outcomes with costs to allow for cost benefit trade-off analysis. The other relates to the consideration of parameter sensitivity. This is an issue that has not been considered in this document. This will help to focus the data gathering activities on those parameters with greatest sensitivity.

The SIC method is demonstrated as providing a simple, flexible and cost effective approach with which to compare complex military systems.

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19. ABSTRACT This document provides a generic, efficient and cost-effective method of comparing system instantiations. It gives a unique view of a complex system by considering how well the system supports the overarching aim. The method proposed was developed from a requirement to undertake evaluations of complex military systems, in particular those associated with command and control. To illustrate the generic nature of the method, it is introduced using three very different systems. A military headquarters is then used as a more comprehensive example of how the method can be applied.				